PAWN, AN INDUCTIVE STORAGE PULSED POWER GENERATOR FOR HIGH POWER APPLICATIONS

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Abstract

A pulsed power generator, Pawn, has been assembled at the Naval Research Laboratory. It employees inductive energy storage and opening switch power conditioning techniques with high energy density capacitors as the primary energy store. The energy stored in the capacitor bank is transferred to a vacuum inductor in $\approx 15\ \mu s$. Wire fuses provide the first stage of pulse compression. Further power conditioning is obtained with a plasma erosion opening switch.

Initial results are encouraging. Starting with a $\approx$38-kV charging voltage on the capacitor bank, a 0.26-TW, 85-ns full width at half maximum electrical power pulse was delivered to an electron-beam diode. The final values of dI/dt and peak load voltage were higher than the initial values by factors of $\approx$65 and $\approx$11, respectively. A detailed analysis indicates how this performance can be improved.

Introduction

Inductive energy storage in combination with opening switch power conditioning techniques offers several attractive features for pulsed power applications when compared with conventional, capacitive technology.[1] These advantages include compactness and low cost of the primary energy store. Also, because only the last stages of the power conditioning sequence involves high voltage, complexities such as oil insulated Marx banks, water filled pulse forming lines, and power limiting interfaces can be eliminated. The technical difficulty with this inductive approach for some pulsed power applications has always been obtaining the required power conditioning, i.e., generating >1-TW, <100-ns pulses. This must be accomplished by a sequence of opening switches electrically in parallel with each other and the load. Each successive switch opens faster, resulting in higher and higher voltage. The challenge is to understand the physics governing the opening switch behavior well enough to design a system for which the interaction between the system components efficiently produces the desired power pulse.

An experimental, inductive storage, pulsed power generator, Pawn,[2] has been assembled at the Naval Research Laboratory (NRL) using a low voltage, compact capacitor bank as the primary store (1 MJ at 44 kV). In this paper the Pawn system is described, the high power results are presented, and the performance is analyzed. Based on the analysis, suggestions are made to improve the system performance.

System Description

The system[2] is schematically depicted in Fig. 1. The pulse generator comprises a capacitor bank,[3] a vacuum coaxial inductor attached to the capacitor bank via parallel plates, a low voltage vacuum feedthrough (not shown), a fuse[2,4] contained within a pressurized gas enclosure, a vacuum flashover (closing) switch (VFS) that can be command or self-triggered,[5] a plasma erosion opening switch (PEOS),[6] and an e-beam diode load. The capacitor bank[3] has 20, 52-μf capacitors connected in parallel. At the maximum rated charge voltage of 44 kV, one capacitor stores 50 kJ. They are connected, in groups of five, to the common parallel plate feed through a pressurized, railgap switch (RGS). The coaxial energy storage inductor is made of aluminum tubing with welded flanges and connects to a load coupling "tee." This tee section provides mounting surfaces for connecting two coaxial fuse enclosures and the coaxial output assembly. The assembly contains the VFS, the PEOS, and the e-beam load.

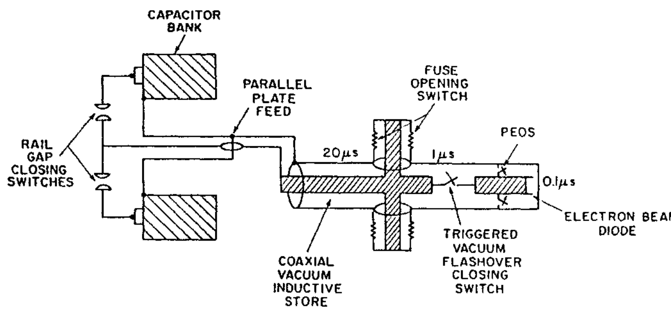

Figure 1. Schematic illustration of Pawn system.

An equivalent circuit for Pawn is shown in Fig. 2. The bank capacitance, C, is 1025 μF. The total system resistance R_T includes skin, RGS, and internal capacitor resistances totaling 1.1 mΩ, and the resistance of current limiting resistors of 3.6 mΩ. These so-called "safety" resistors are in the circuit to limit the current drawn from the capacitor bank in the event of faults. The internal inductance of the bank, L_B, includes the switches and transmission plates and is estimated to be $\approx$40 nH. The calculated inductance of the coaxial storage inductor is $L_S \approx 70$ nH. The fuse resistance is represented by $R_F(t)$. For the parameters given here and with a $\approx$38-kV, capacitor charge voltage, the current flowing from the capacitor bank, I_B, and through the fuse, I_F, reaches a broad peak $\approx 13\ \mu s$ after the closure of the RGS. The presence of the series fuse inductance, L_F, is a consequence of the particular geometry chosen for Pawn (see Fig. 1). The energy stored in it is used by the fuse to reach its high resistance state at opening.[4] The calculated inductance of the two, parallel fuse assemblies for the 50-cm long fuse is $L_F \approx 65$ nH.

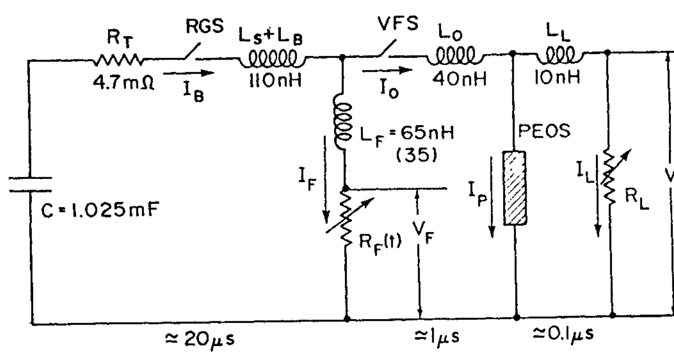

Figure 2. Equivalent circuit for Pawn System.

The energy stored inductively in $L_S + L_B$ is "conditioned" by both the fuse and PEOS. The fuse consists of an array of parallel copper wires.[2] As energy is dissipated by Joule heating, the fuse changes from a highly conductive medium to a highly resistive medium.[4] At the appropriate time the VFS is command triggered and current, I_0, is transferred to the PEOS through the coupling inductance, $L_0 \approx 40$ nH. Typically, the PEOS plasma sources are triggered 2.5-5 μs before the VFS closure. The PEOS conducts current, I_P, for up to $\approx 1\ \mu s$,

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14. ABSTRACT
A pulsed power generator, Pawn, has been assembled at the Naval Research Laboratory. It employees inductive energy storage and opening switch power conditioning techniques with high energy density capacitors as the primary energy store. The energy stored in the capacitor bank is transferred to a vacuum inductor in "'15 ps. Wire fuses provide the first stage of pulse compression. Futiher power conditioning is obtained with a plasma erosion opening switch.

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depending on the time delay between plasma source and VFS triggering, the type of plasma source, and the PEOS electrode geometry.[6] During this time current in the fuse decreases. The PEOS then opens rapidly ($\approx$100 ns) transferring current, I_L, to the load, R_L. We have estimated the coupling inductance between the PEOS and load to be $L_L \approx 10$ nH, small compared with the other inductance values.

For the PEOS, nine flashboards, each driven by a 0.6-μF capacitor charged to 25 kV, were located $\approx$22 cm from the load and azimuthally distributed at a distance of 12 cm from the 11.75-cm radius cathode (center conductor). A mask, with an 8.4-cm wide opening was placed over the PEOS anode (transparent outer conductor). The radial gap between the PEOS anode and cathode was 3.2 cm. For the data presented here, the load consisted of an e-beam diode of 11.75-cm radius with 50-μm thick tantalum foil for the anode.

The diagnostics consisted of a Rogowski coil to measure the capacitor bank current, two B-probes in the vacuum inductive store region, four B-probes in the fuse tee vacuum region (2 for each fuse), two B-probes between the VFS and PEOS, four B-probes on the capacitor side of the PEOS and four B-probes on the load side of the PEOS. A resistive voltage divider was used to measure the fuse voltage. The voltage across the PEOS, V_S, and the voltage across the fuse, V_F, are related by

$$V_S = V_F + L_F(dI_F/dt) - L_0(dI_0/dt). \qquad (1)$$

By measuring V_F, I_F, and I_0, V_S can be calculated. L_L is relatively small, so $V_S \approx V_L$, where V_L is the load voltage. Because e-beam diodes were used for loads, V_L could be inferred using ratios of filtered scintillator-photodiode x-ray detectors. The two methods generally agree to within 15%.

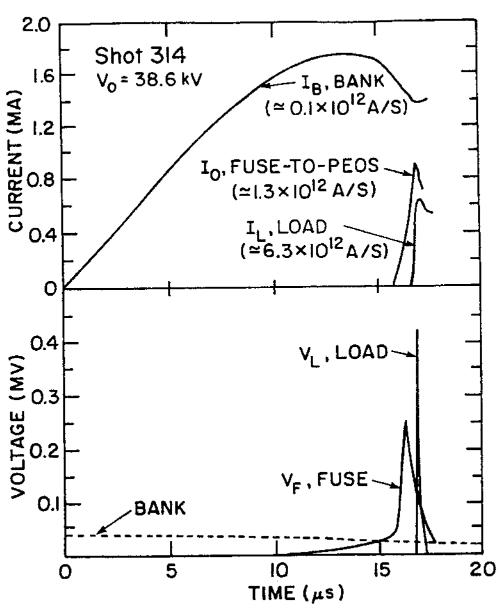

Figure 3. Currents and voltages for a Pawn shot illustrating inductive storage principles.

System Operation

The basic principles of inductive storage with staged opening switch power conditioning are illustrated by the Pawn data shown in Fig. 3. Displayed in the upper portion of the figure are the measured currents I_B, I_0, and I_L as functions of time. In the lower portion, the capacitor bank voltage, V_F, and V_L ($\approx V_S$) are shown as functions of time. The voltage and average dI/dt increases at each stage of power conditioning, with high voltage achieved only at the load. I_B reaches a peak value of $\approx$1.75 MA at $\approx$13 μs, measured from the initiation of the bank current. This is an average dI/dt of 0.1x10^{12} A/s. The fuse generates a 240 kV pulse that transfers current I_0, upon VFS closure, into the next stage of the system. The VFS closes at $\approx$15.8 μs, so the long precursor, or "prepulse," on V_F (associated with the fuse changing from solid to liquid phase) is isolated from the PEOS. After conducting for nearly 1 μs the PEOS opens, delivering a high power pulse to the load.

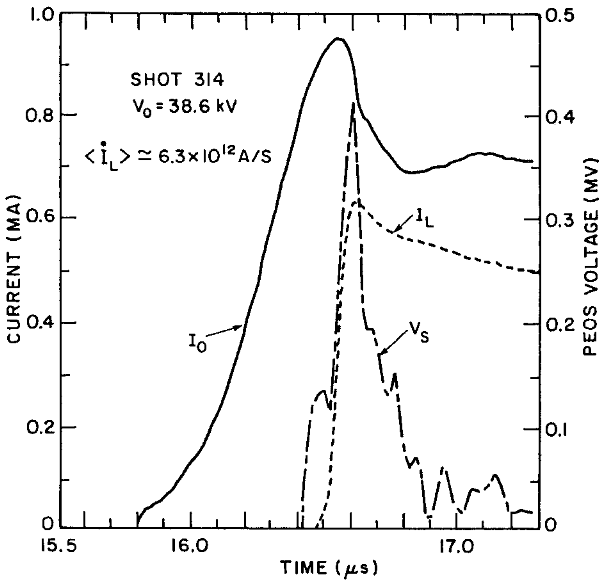

Figure 4. Fuse output current, load current, and switch (load) voltage on an expanded time scale.

In Fig. 4, I_0, I_L, and V_L are shown as functions of time for the same shot on an expanded time scale. The peak values of V_L, $\approx$410 kV is a factor of $\approx$11 greater than the initial charging voltage. The fuse gives a voltage gain of $\approx$3, while the PEOS increases the voltage by an additional factor of $\approx$3.5. The average dI_L/dt, $\approx$6.3x10^{12} A/s, represents a total system gain of $\approx$65. Here, the fuse is responsible for a gain of $\approx$13, while the PEOS contributes a factor of $\approx$5. The load power, P_L, obtained from I_L and V_L of Fig. 4, and energy, E_L, are plotted as functions of time in Fig. 5. The peak value of P_L is 0.26 TW with a $\approx$85-ns full width at half maximum (FWHM). After 200 ns, 27 kJ was coupled to the load.

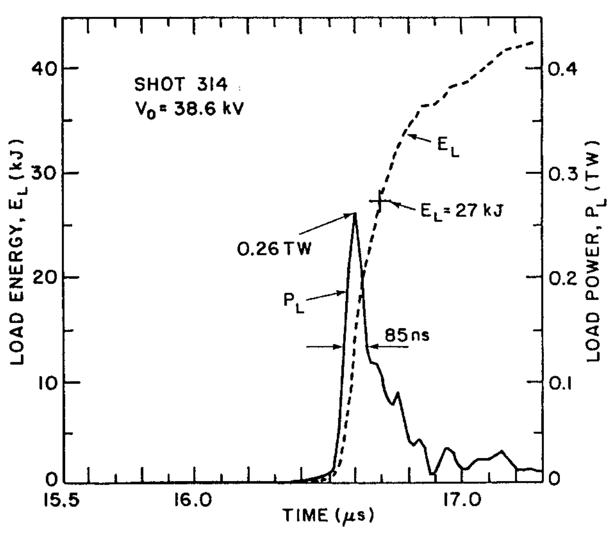

Figure 5. Power and energy delivered to the e-beam.

System Analysis

A detailed energy inventory was performed for shot 314 at $t = 16.7\ \mu s$, approximately 200 ns after current begins flowing in the load. The current limiting resistors dissipate nearly 15% of the initial stored energy. It may be possible to operate with a lower resistance. However, this has not as yet been tried. The remaining energy is apportioned approximately as follows: 40% dissipated in the fuse, 25% left in the capacitor bank, 20% left in the system inductances, 5% dissipated in the system resistances, 5% dissipated in the PEOS, and 5% dissipated in the e-beam load.

The largest energy loss occurs as a result of the resistive loss in the fuse. There are several ways in which this loss may be reduced. Tests performed on a small scale apparatus suggested that the highest voltage, smallest FWHM fuse voltage pulse with the best recovery properties would be obtained on Pawn when ≈3 times the energy required to do the inductor-to-inductor transfer was dissipated during fuse melting and vaporization. With further fuse development, this stringent requirement could be relaxed. It also may be possible to replace the fuse with another long conduction time opening switch, ideally operating in vacuum, that has less loss associated with it. This option requires a fairly intense research effort, although some work has been done in this area.[7]

A large amount of energy remains unused, residing in the capacitor bank and system inductances. Increasing the fraction of energy transferred from the capacitors to the inductances involves sizing the fuse differently. This may be self-defeating, because increasing the fuse cross section to carry current longer also means more energy must be invested in vaporizing the additional mass. For any gain in available energy to be of consequence, it must be coupled successfully to the load. For example, in the data shown here, four times more energy remains in the inductances than was delivered to the load. This results from the comparable values of the PEOS opening time and the diode closure time.

The energy dissipated in the system resistances is unavoidable. This loss scales directly with conduction time and the square of the current. It may be significant for higher energy, long conduction time systems. Almost as much energy is dissipated in the PEOS during opening as is delivered to the load. This is a result of the PEOS opening in a time comparable with the characteristic system L/R time during opening.

To evaluate various approaches for improving system performance, a transmission line circuit code was used with a time dependent, empirical model for the fuse resistivity, an ad-hoc, constant rate of rise model for PEOS resistance as a function of time, and an assumed constant 0.65-Ω load. The calculated and measured waveforms agree. The switching performance and load were then varied to see what would be obtained if the system elements could be made to behave differently. For the same charging voltage and fuse behavior, allowing the PEOS to conduct ≈50% longer and open to a 1-Ω diode at a ≈4 times faster rate results in a 0.7-TW pulse. Peak power reaches 0.9 TW for this case by further assuming that at the time of PEOS opening the fuse resistance is high enough (several ohms) that $I_F \approx 0$. Note that Pawn occupies <5% of the volume required by a conventional, capacitive system capable of generating ≈1 TW.

Summary

A pulsed power generator employing inductive energy storage and opening switch power conditioning techniques has been assembled at NRL and is now operational. Initial, non-optimized results with the PEOS are encouraging. Starting with a ≈38-kV charging voltage on the capacitor bank, a 0.26-TW, 85-ns FWHM electrical power pulse was delivered to a an electron-beam (e-beam) diode. The peak diode voltage was ≈410 kV, a factor of ≈11 gain over the initial bank voltage. The final dI/dt was 6.1×10^{12} A/s, which represents a system gain of ≈65. We have demonstrated on Pawn, in a parameter regime appropriate for scaling to higher power systems, that the low voltage, staged opening switch power conditioning approach is a feasible option for the generation of high power electrical pulses from inductive generators. The system has been analyzed, and directions for improved operation defined. Work is now underway to improve this performance. This includes improving the PEOS and may necessitate a different approach for the first stage switch.

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References

1. R.E. Reinovsky, W.L. Baker, Y.G. Chen, J. Holmes, and E.A. Lopez, 4th IEEE Pulsed Power Conference, Albuquerque, NM (1983), T.H. Martin and M.F. Rose, Eds., IEEE Cat. No. 83CH1908-3, p. 196.

2. R.J. Commisso, J.R. Boller, G. Cooperstein, R.D. Ford, D.J. Jenkins, J.C. Kellogg, P.J. Goodrich, D.D. Hinshelwood, W.H. Lupton, B.V. Weber, and J.D. Shipman, Jr., Naval Research Laboratory Memorandum Report 6129 (1988).

3. J. Shannon, P. Krickhuhn, R. Dethlefsen, O. Cole, and H. Kent, 5th IEEE Pulsed Power Conference, Arlington, VA (1985), M.F. Rose and P.J. Turchi, Eds., IEEE Cat. No. 85C2121-2, p. 26.

4. C. Maisonnier, J.G. Linhart, C. Gourlan, Rev. Sci. Instrum. 37, 1380 (1966).

5. J.C. Kellogg, J.R. Boller, R.J. Commisso, R.D. Ford, D.J. Jenkins, W.H. Lupton, and J.D. Shipman, Jr., these conference proceedings.

6. B.V. Weber, R.J. Commisso, G. Cooperstein, J.M. Grossmann, D.D. Hinshelwood, D. Mosher, J.M. Neri, P.F. Ottinger, and S.J. Stephanakis, IEEE Trans. Plasma Sci. PS-15, 635 (1987), and B.V. Weber, et al., these conference proceedings.

7. P.J. Turchi, M.L. Almi, G. Bird, C.N. Boyer, S.K. Coffey, D. Conti, J.F. Davis III, and S.W. Seiler, IEEE Trans. Plasma Sci. PS-15, 747 (1987).